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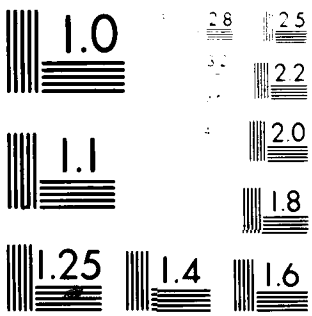
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The fundamental mechanisms of the interaction of electrical discharges of the glow type and the fluid mechanics normally found in electric discharge lasers have been studied in an effort to improve their performance capability. Basic information on these devices was obtained via small-scale experiments at the University of Washington. An alternative method of phase compensation for laser beams using the refractive properties of gas jets was also investigated. The amount of beam degradation produced by turbulent shear layers in the jets was

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~~20.~~ studied also. The experimental investigation of this beam degradation mechanism constitutes much of the effort in the project. Theoretical calculations detailing the effects of mixing of dissimilar gases at low Mach number have been carried out.

High-power laser-mixing flows have been studied by numerical, analytical, and experimental techniques. The models for wave decay in supersonic cavity flows have been extended, optical sensitivities calculated, and experiments conducted using a laser interferometer. Calculated thermodynamic parameter history through decaying wave systems has been used with simple HF reaction models to study strongly-coupled reaction shocks. A systematic study of the sensitivity of HF laser performance to fluid process assumptions has been carried out, with emphasis on power extraction measurements from a versatile shock/Ludwieg tube laboratory laser.

RESEARCH ON FLOW PHENOMENA RELATED TO THE HIGH POWER LASER

The theoretical and experimental research in this project can be grouped into three broad categories: the aerodynamics of e-beam stabilized discharges; fluid mechanical optics; and expansion and cavity mixing processes in flow lasers.

I. AERODYNAMICS OF E-BEAM SUSTAINED DISCHARGES IN FLOW

Background

High pressure, large volume glow discharges have become an important topic of study in recent years due to the development of high power electric lasers. The theoretical performance of laser systems using a combination of electric discharge and flow are very attractive,[1] provided certain problems, not the least of which is the tendency of a glow to arc transition, are overcome. For cw and long pulse discharges this glow to arc transition undoubtedly due in part to undesirable gas motion as a result of fluid mechanical interaction with the discharge.

The fundamental mechanisms of the interaction of electrical discharges of the glow type and the fluid mechanics as normally found in electric discharge lasers have been studied in an effort to improve their performance capability. Some basic information on these devices has been obtained via small-scale experiments at the University of Washington, where a small scale apparatus has been built to simulate an e-beam controlled discharge in flows. The flow and discharge characteristics of a cw electric laser are simulated using a combination of long duration pulsed flow and electric discharge. The experimental setup is composed of three main systems which can be controlled independently: the flow system, the electron-beam gun, and the main discharge.[2] The flow is provided by a Ludwieg tube and nozzle arrangement. Premixed gas is expanded via a contoured 2-D nozzle to various temperatures and pressures. After an initial transient of 2 msec duration the pressure in the plenum chamber becomes nearly constant, giving a testing time in excess of 8 msec at a supersonic flow condition of $M = 3.2$.

An electron beam gun, which is located above the test section, is used as an external source of electrons that preionize the gas and provide the necessary conditions to sustain the discharge. A plasma diode e-beam gun, is adapted and used for its high current density emission. It can operate with current density outputs more than one order of magnitude greater than that of thermionic guns. This permits a small experiment to simulate the power loading of a larger thermionic system. Current densities from 1ma/cm^2 to 30 ma/cm^2 at voltages of up to 135kv have been measured from the diode without foil failure. These current densities are higher than contemplated for cw or high repetition rate systems. Thus high electron densities and high sustainer current is available to pump the system rapidly.

The main discharge is applied across two flush mounted electrodes in the test section. The initiation and termination of the discharge is done independently of the e-beam. The flow test section is 4 cm in height and 20 cm wide with the electrode spacing equal to the test section height. The discharge dimensions are 4 cm in the flow direction and 14 cm transverse to it, thus giving a 3 cm insulating region on each side of the discharge to prevent interaction with the side wall boundary layer. At the highest e-beam current levels, power densities in the discharge are in excess of 10^7 w/liter-amagat.

Research Activities

In the course of operating the discharge, measurements of the cathode phenomena without flow were extensively investigated and reported.[3] Interferograms in the no-flow case have also shown severe heating of the gas near the electrode edges. These measurements have also clearly shown extensive cathode fall heating and the cathode shock wave. Of particular interest is the rather large region near the cathode in which a non-uniformity density appears. This density field is probably due to heat diffusion phenomena, but it is orders of magnitude thick for the time scale of the study.[3] There are two mechanisms considered likely for this process. One is a Rayleigh-Taylor type instability, due to the heated less dense thermal layer expanding and driving the more dense core gas. There is a large initial acceleration in the thermal layer (order 10^6m/sec^2). The other possible mechanism is a non-uniform non-steady discharge current

causing localized heating in the cathode fall, giving the appearance of a convectively enhanced diffusion layer.

Since the cathode fall is extremely thin, it may be considered to be a surface heating phenomenon, and a surface heating experiment[4] has been designed to simulate the rapid temperature rise times observed in this region without interference from other discharge phenomena. An electric current is passed through a thin electrically conductive surface layer, heating it to produce surface temperatures of several hundred degrees Celsius in several hundred μsec. This enables observation of the density profiles near the heated surface without interference from other processes occurring in the discharge. Results showed that uniform surface heating (simulating uniform discharge current distribution) leads to thin thermal layers that are purely one dimensional in nature. If hot spots are created on the surface (simulating current attachment spots on the cathode), the resulting thermal region grows much more than one order of magnitude faster in the vicinity of the spots than with uniform heating. This experiment[4] showed that the cathode surface phenomenon is probably not strictly fluid mechanical in origin. Rather nonuniform heating due to current spotting on the cathode is the most likely cause. As a result of the preliminary investigation, the discharge attachment is being studied in more detail by measuring the current distribution over the cathode as a function of time. Specifically the size, current density, and distribution of the current attachment spots under various conditions are being measured.

Previously, extensive series of density measurements of the effect of the discharge on the flow field were taken using a laser holographic technique. When a flat plate having the same planform as the cathode surface is placed above the wall boundary layer to serve as a sustainer electrode, the effect of the cathode on the boundary layer can be clearly seen.[3] Without a discharge, a very thin boundary layer is observed, as would be expected because of the nearness of the leading edge. If the plate serves as the anode, there is no change in this boundary layer when the discharge is applied. When an equal voltage with opposite polarity is applied, the boundary layer thickness triples. Increasing the power further to the discharge results in an

even thicker boundary layer. An oblique shock wave at the leading of the cathode edge is clearly enhanced by the discharge. The relative density jump across the wave increases from 5 to 15% when sufficient power is applied; a change in optical path which is significant when related to far-field performance of a laser. In removing the cathode from the existing boundary layer in the test section, the power loading per unit volume can be increased by a factor of two before arcing occurs. Energy input reached 1000 J/lit.ama. corresponding to $5(10^6)$ w/cm^3 before the arc was developed. This is a significant improvement in the flowing gas case and suggests that additional gas are possible when boundary phenomena in discharges are fully understood. Preliminary modeling of the optics of a supersonic flow field induced by nonuniform heating was begun and these calculations are reported in a thesis by Farve.[5] Compressible boundary layers are being analyzed with severe heat addition in order to predict boundary layer growth over the cathode. This should result in a MS thesis this year.

Pressure histories in the vicinity of the discharges have been measured. These histories have also been used to determine the fraction of the pump energy going into gas heating. Pressure histories were measured in discharges through nitrogen having durations between 100 μsec and 300 μsec. The measurements employed piezoelectric transducers mounted near the main discharge cathode to detect the pressure rise due to volumetric heating by the discharge. The experiments were conducted in initially stationary nitrogen and in quasi-steady $M = 3.2$ flow. Pressure measurements are quite difficult to obtain in the noisy electrical environment. However from many of the experiments where the discharge was applied for long flow times, it is observed that steady-state values of pressure were reached after 300 μsec approximately, or 5 flow times, although the functional dependence on discharge parameters was not investigated.

The method of characteristics for non-steady flows was used to compute simulated pressure histories based on a one-dimensional model of volumetric heat addition to a perfect gas. It was determined that the pressure maxima may be used to find the variation of electrical power converted to thermal with the ratio of electric field to number density. The simulated pressure histories were used to calculate this

and to find the spatial distribution of electrical heating. These results were reported in a thesis by Margalith[2] and Smith.[6]

II. FLUID MECHANICAL OPTICS

Phase Correction using Gas Jets with Varying Refractive Indices

Phase distortion of a laser beam can substantially reduce the maximum power density to which the beam can be focused; this is a significant disadvantage in many applications. Phase distortion of a beam can occur, for example, in the laser resonator or in the atmosphere due to turbulence or thermal blooming. Such phase distortion can, at least in part, be compensated for by adaptive optics. Conventional adaptive optics[7], usually deformable mirrors or Bragg cells, have a relatively low power density capability ($\sim 10^4$ w/cm^2 maximum). The use of gas jets with varying refractive indices placed in the path of the laser to act as phase shifting elements would allow phase corrections to be applied to beams with power densities up to 10^8 - 10^9 x/cm.[2] For this concept to be useful, it is necessary that the unwanted phase errors caused by the jets due to turbulent shear layers and waves can be kept within certain bounds and that means of rapidly changing the refractive indices of the jets can be developed

During the past contract period we have constructed a number of different devices for testing the concept using low-power visible lases as probes. In particular, a Mach Zhender interferometer for measuring the phase distortion introduced by the free jets in the near-field has been constructed. The necessary supersonic flow apparatus to provide free jets with cross sections on the order of one centimeter was completed. Lastly a telescope and other optical apparatus have been built so that the far-field patter of the laser beam can be observed within distances on the optics test table.

The first experimental work undertaken was the investigation of the optical quality of single $M \sim 2$ jets of helium, nitrogen, argon and a 62% helium - 38% argon mixture. The mixture was chosen so that its refractive index matched that of the ambient air. As stated previously, these jets were studied using long exposure near-field interferometry and by taking far-field power-in-the-bucket measurements. We have since obtained "stop-action" near-field

interferograms (using a Q-switched ruby laser) and high-quality schlieren photograpphs of the jets and have extracted Strehl ratio values from the power-in-the-bucket data taken earlier as part of a masters thesis.[8] A paper[9] discussing all the results on the single M ~ 2 jets appeared in Applied Optics. It was found that the index-matched M ~ 2 jet had the highest optical quality, as expected. Strehl ratios up to 0.92 were obtained with the index-matched jet, indicating that, at least for this particular jet, beam degradation due to shear layer turbulence and waves is tolerably low. Near-field phase error measurements were found to be reasonably consistant with the measured far-field Strehl ratios.

A simple correlation of the far-field Strehl ratios with the refractive indices of the gases and the shear layer thickness was found to be unsatisfactory. In the course of our work, a number of reasons for the failure of this simple type of correlation have come to light. These are discussed in Ref. 14. It seems likely that a detailed knowledge of the shear layer structure, in particular, of the amplitudes and scale lengths of the refractive index fluctuations, would be necessary to allow good correlations and predictions of optical quality to be made. A number of ways of improving the optical quality of shear layers which have come to light during our past work has been suggested[10] is of course, not only applicable to gas jet phase control systems, but also to aerodynamic windows and shear layers inside laser resonators.

A two-element gas jet phase control "array" was built and tested. The elements osf this "array" were the jets from two M ~ 1.6 nozzles. One nozzle was simple, producing a jet with a fixed phase shift. The second nozzle was supplied from two plenums filled with different gases. The phase shift produced by the second nozzle could be varied by moving a small flutter valve dividing the two plenums. The working gases were helium and 62% helium/38% argon. Results of our experiments on the two-element array are presented in Refs. 11 and 12. The phase shift produced by the variable nozzle could be changed by about 4π. For a number of different settings of the phase shift difference between the two jets, the optical quality of a beam traversing the jets was studied in the near-field interferometrically and with schlieren

photography and in the far-field by simple photography. In a second series of experiments, a phase error was deliberately applied to the input beam to the jets. Qualitative compensation, by the jets, for this phase error was demonstrated in the near-and far-fields. The far-field Strehl ratio, however, for the compensated beam was rather poor. It is believed that the main reason for the poor Strehl ratio was the presence of waves in the jets, especially those produced at the end of the splitter plate. One reason we had originally chosen a system operating at $M \sim 2$ for study was on account of its high frequency capability. From the above result, it is now evident that, in a multiple jet system, beam degradation by waves can be quite detrimental. Partly from these experimental results, and partly from the theoretical part of our work, we believe that a practical gas jet phase control system probably should operate at high subsonic Mach numbers to eliminate waves. The loss in frequency capability is not severe, being about 30 - 35%.

At this point in the work, the most promising gas jet configuration for (a single array) a practical phase control system appears to be that shown in Fig. 1. The variable density jets would be premixed with the plenum and all the jets would be high subsonic speeds. Beam degradation at the gas interfaces would be kept under control by velocity matching at interior interfaces (BC,CD,CH, etc.) and index matching at the two exterior interfaces (AB and HI). The velocity and index matching are believed likely to be necessary to allow high Strehl ratios to be obtained with subsonic jets, since it is well known[13] that shear layers tend to be thicker at subsonic speeds than at higher Mach numbers. A triple convergent nozzle has been constructed and will allow the simulation of either three variable index jets (such as jets D,E and F) in Fig. 1 or of one variable index jet and the two buffer jets (dash-dot rectangle in Fig. 1). The first tests on the triple convergent nozzle consisted of operating all three jets with the same gas and at the same velocity, and studying the spreading rate of the external shear layers for seven different gases ranging from helium to sulfur hexafluoride. The triple nozzle was found to perform well and excellent shear layer spreading rate data was obtained. This data should be useful in the design and prediction of

shear layers in aerodynamic windows and inside laser resonators, as well as for phase control systems. This data will be submitted for publication shortly.

A simple theory based on the Prandtl mixing length model has been developed which predicts many aspects of shear layer behavior remarkedly well. Theoretical calculations detailing the effects of mixing of dissimilar gases at low Mach number using this model has been carried out and submitted to The Physics of Fluids.[14] Likewise, papers describing calculations concerning the potential phase correction using inviscid free jets have been published.[15,16] In Ref. 16 it was shown that crossed arrays of jets have the potential of reducing lower order mode errors significantly and that they approach that of deformable mirrors leaving the same number of active controls.

Gasdynamic Light Guide

The work reported here is a continuation of the work of AFOSR grant #74-2650. The work involves the study of the light guiding regions which can be created (due to density and refractive index gradients) in the throat region of a radial flow nozzle whose throat lies on the arc of a circle. The light guides which have been studied have throat heights of 0.40 mm, throat radii of 76 mm and are operated with dry nitrogen at pressures of 30 to 100 atm. Light guides with sector angles of 90° and 360° were studied. As stated in the final report for grant #74-2650, tests of a 90° light guide with a simple convergent nozzle profile have allowed a good understanding of the operation of a gasdynamic light guide to be obtained and have demonstrated beam transmissions greater than 99.5% at low beam power densities. These results have since been published.[17] Work on the same device at high beam power densities has also been completed and published.[18] Our high power density work has shown that up to power densities of 10^7 w/cm^2 averaged over the light guiding region and 3 x 10^8 x/cm^2 at the beam focus, there is no observable reduction in the light guide transmission attributable to the high power densities, and transmissions of 99% or greater can be obtained. These results confirmed the expected continued usefulness of gasdynamic light guides at very high power densities.

With the original 90^o light guide, the quality of the exiting beam was observed to be rather poor[17]. We have since designed, built, and conducted tests on an improved verion which has carefully profiled nozzle contour. This has been designed to produce a good approximation of the refractive index profile used in graded-index glass fibers in the flowing gas. Tests on this device have shown a greatly improved quality of the exiting beam. Fig. 2 shows photographs of the beam exiting from the devices at comparable operating conditions. The well-defined exiting beam obtainable with the improved device is roughly the size theoretically expected for a TEMoo mode in the light guiding region. Results on the latter device may be published shortly.

A 360^o device with a convergent-divergent nozzle was designed and built; tests were made to attempt to demonstrate the storage of light by aerodynamic means. The tests consisted of passing the focused beam from a Q-switched ruby laser through the light guiding region at a grazing angle, and monitoring the light guiding region on the other side of the device with a photomultiplier for evidence of light storage. It was hoped that a small fraction of the ruby laser pulse could be scattered into the light guiding region by random refractive index fluctuations, trapped for perhaps many hundreds of circuits, and observed as it slowly scattered out of the device. However, after several month's work developing the experimental technique and making measurements, we were unable to obtain evidence of light storage. (The measurements are difficult because the output power from the device, in this simple, proof-of-principle mode of operation is estimated to be 12 or more orders of magnitude weaker than the input power). These negative experimental results are believed not to necessarily demonstrate the failure of this concept of light storage, but may indicate that it is necessary to deliberately disturb the light guiding region to allow significant amounts of light to be injected and removed.

III. EXPANSION AND MIXING PROCESSES

Wave and Wake Decay in the Cavity

High power lasers use a variety of nozzle/injector configurations, frequently with different scales and different gases at different conditions. The flow downstream of each individual expansion is quickly confined to a channel by the neighboring flows, and this most typically requires shock turning into the channel with a subsequent decaying wave system. A first step in understanding such flows is to study the case of a single gas issuing from an array of identical nozzles.

The wave system has recently been worked out for a close-packed array of matched conical source-expansions of a single gas.[19] The symmetry in planes parallel to the nozzle exit is hexagonal in this case, and the basic problem to be solved becomes source flow into a channel with parallel walls and a 30^{o} right-triangular crossection. Shock sheets are formed and reflect down the channel as a result of the velocity tangency condition on the tangent and inclined sides, and the cavity flow is filled with these folded shock systems packed together. The small perturbation model that has been developed provides a convenient closed-form solution to this complex flow.[19] It shows a periodic pattern of flow nonuniformity on the scale of the downstream shock cells, on which is superimposed a general decay. There are cross-stream entropy differences due to accumulated processing by different strength shock waves. These remain after the wave system has decayed to Mach waves, and can exceed the nonuniformity level due to the viscous wakes. The model is uniformly valid in both the near-and far-field, and has been developed for 2-D expansions in addition to close-packed 3-D. In all cases the strength of the nonuniformities is simply related to the angle of the initial source expansion, and method-of-characteristics calculations can be used to determine an effective source angle for a general expansion contour. In addition to expansion angle, the solutions readily show the effects of such parameters as nozzle scale, Mach number, and gas specific heat ratio. This work has been presented at a specialist conference and is being written up for journal submission.[20]

A series of ruby-laser holographic-interferometer measurements were made of the flow downstream of nozzle arrays mounted in the 7.5 x 10.0-cm test section of a Ludwieg tube. Ten-degree half-angle conical expansions of area ratio 10 were drilled with close-packed geometry in each of three different nozzle plates. The test section could be rotated in the plane parallel to the nozzle exit so as to change the angle the interferometer optical axis made with the flow pattern. The interferograms generally showed fringe excursions that were repeatable across the flow on the expected nozzle scale, with amplitudes that decreased with downstream distance. The amplitudes and patterns were also strongly dependent on the angle between the flow pattern and the optical axis. For the angle where the amplitudes were predicted to be a maximum by the wave model, the fringe amplitude was observed to repeatedly decay to zero and build up in reverse on a downstream scale equivalent to a Mach cell. Computer-generated interferograms using the wave model were in striking agreement with the experimentally observed patterns and their downstream decay. Further, the measured maximum fringe amplitude dropped as much as a factor of five as the optical axis angle was increased, building back as the angle reached 30°, again in agreement with the wave model. These results are available in thesis form and have been reported at a student conference.[21]

It was noted, however, that the experimental interferograms did not show the repetitive amplitude buildup and decay characteristic of the wave model when the optical axis angle was changed. Instead, they showed fringe amplitudes that changed very slowly, more reminscent of wake effects. Such wakes were modeled as being fed from the boundary layers in the nozzles and the losses at the nozzle bases. The former was calculated from laminar compressible boundary-layer theory, while the base pressure was selected between reasonable limits. The appropriate fraction of the boundary-layer momentum loss was then added to each base loss to produce an axisymmetric wake extending from the center of each base region, i.e., at the vertices of the hexagonal cells in the case of the close-packed array. The wakes were assumed to be turbulent and were treated with a simple mixing length model, while compressibility was handled with a transformation of the transverse dimension.

The wake model predicts the 30^o angle case quite well, and fortunately has optical cancellation effects at the other angles such as to reduce its importance relative to the waves. While some discrepancies remain to be clarified, superimposing the wave and wake models does explain a remarkable number of features of the flow. An abstract describing this work has been submitted to an international symposium.[22]

The models for single gas wave and wake systems serve as a logical starting point for the study of more complex mixing flows. These models may be applied to adjacent channels with different gas conditions as a first-cut try. However, many flows will need higher-order approximations which involve channel boundary change in response to the pressure fields developed. It turns out to be relatively simple to extend the wave model to boundaries with angle changes at shock junctions. A version of this approach has been explored for the case of the chemical laser with constant-angle channel constriction brought about by the displacement effect of heat release at the mixing boundary. Calculations for the 2-D flow from 10^o half-angle nozzles show that even a 1^o constriction can introduce a substantial compression of the downstream wave pattern, significantly changing the pressure and temperature fields. The expansion-generated wave system can have a dramatic affect on laser kinetics, and thus modifications of those waves due to boundary changes can be important.

Cavity Mixing Layer Flows

Compressible dissimilar-gas mixing layers are themselves of interest for laser flows, and a numerical study was recently completed using a modern space-marching form of the MacCormack algorithim to solve the parabolized form of the governing field equations.[23] The method can thus compute viscous flows with shocks and expansions efficiently. Prandtl's constant-exchange eddy-transport model was used to explore mixing flows of interest to chemical lasers, and the work is being prepared for publication. A much more physical approach was worked on in conjunction with personnel at the California Institute of Technology. In this, the concept of gradient diffusion was argued to be inapplicable to turbulent shear layers, and a new model based on experimentally-observed coherent structures was proposed for treating

molecular mixing and chemical reaction at high Reynolds number. The work was recently presented and has been accepted for journal publication.[24]

The chemical-laser flow-modeling facility constructed earlier has been extensively used to study the effects of fluid environment on overall laser performance. It consists of a 5 x 20 x 750cm shock tube in which various oxidizer mixtures are shock heated and dissociated, and a parallel 7.5id x 600cm Ludwieg tube which serves as an unheated fuel reservoir. Operation is timed such that these gases expand together through alternate columns of conical nozzles in a plate array feeding a 5 x 20cm test-section and cavity. Two nozzle plates were manufactured using individual 10^{o} half-angle expansions of area ratio 10 and exit diameter 0.5cm, in close-packed geometry, one with a minimum 16% base area, the other with the columns spaced to produce a 70% overall base area. Both nonreacting and reacting gas pairs have been used; in the latter case the gases mix and burn, producing excited reaction products which may be made to lase.

With care for safety and purity, the facility has been run with F_2-A or F_2-He oxidizers and pure H_2 fuel. Overtone emission photographs have served to indicate the general configuration of the reacting layers, and a simple optical setup has been used to extract HF laser power for a variety of conditions. Power temporal histories have been carefully correlated with pressure measurements in order to understand the flow starting process, and the degree to which the facility simulates cw operation. The plateau power was found to scatter a maximum of ±25% from the mean at each of three nominal run conditions, was in general agreement with a quasi 1-D theory being developed, and showed a predicted order-of-magnitude increase when the dilutent was changed from A to He. The latter was due to the fact that increased mixing losses and decreased flow speed caused the lasing to shut off before much gas could be entrained into the mixing layers. The initial phases of these experiments were published in the proceedings of an international specialists' symposium.[25] A more recent presentation updated the work and drew attention to the versatility, safety, and cost effectiveness of this type of facility for studying complex laser flows.[26]

A quasi 1-D model for the HF laser has been developed to respond to the need for a theory that preserves the important physical features of the process without burying them in complex numerical codes. Sixteen input parameters are used. For the reservoir these are the fuel and oxidizer compositions and total pressures and temperatures; for the expansions the wall angles, exit diameters, area ratios of the expansions, a wall recombination parameter, and the base area; and finally, in the cavity the 2-D height of the base-flow recompression zone and its axial location, the degree of base-flow combustion, the total entrainment angle, and the ratio of entrainment angles of the two streams. The nozzle exit flows are first individually mixed to uniform states incorporating viscous and turning-shock losses. The mass in the base flow neck is assumed to have come from equal width layers of these exit flows, to be subsequently mixed with appropriate area change to the base pressure. Each free stream minus its neck contribution then expands in a 1-D fashion into the remaining flow area to a uniform chemically-frozen state downstream, with static pressures now balanced. The shear layer begins with the neck gas, subsequently entraining and instantly mixing free stream oxidizer and fuel at separate rates at each step downstream.

A simplified HF chemistry was chosen for consistency with the fluids model. This has four primary levels pumped mainly by the cold reaction. Deactivation by HF, F, F_2, H and diluent is included for each of the levels, as is recombination of H through collisions with H, H_2 and the remaining species. The 4 pumping, 16 deactivation, and 3 recombination rate constant expressions were taken from standard references. These are incorporated into a simplified laser model which is used at each step in the move-mix calculation.

The model has conservative aspects, such as the instantaneous mixing of the expansion losses at the nozzle exit and the dissimilar gas mixing losses taken at each step in the shear layer. The exit-flow turning shock, the lip shock, and the recompression and reaction shock systems produce an entropy field which increases with x and varies transversely. The fact that there are larger losses along the wake axis than along the nozzle axis is lost to the present model, which treats the effects only in an average sense. This and the

instantaneous shear-layer mixing may counterbalance the conservative assumptions. The model does retain many real features of the laser flow, and is correct in the downstream limit. Transverse boundary-layer scales appear through the neck width, and axial scales through the neck location and the entrainment angles.

The model provides a relatively fast way of calculating laser performance and systematically assessing its dependence on a number of complex field parameters. It was used to study the effects of a separate variation of each of the 16 parameters from a chosen reference condition. Power output was found to depend on all of the parameters and all must be consistently treated. However, the extent of the neck and the degree of preburning in the base region flow was found to be particularly important, as were the relative and absolute shear layer entrainment rates if the nozzle was not already designed for maximum power. Similarly, the total pressure and temperature levels of the oxidizer, its concentration, and the amount of base area in the expansion had strong effects. The work emphasized the sensitivity of laser output to the highly-coupled fluid mechanics and the reasons why. It was recently reported at a national conference.[27] The model continues to show good agreement with experiments carried out using the shock/Ludwieg tube facility,[26] and to be useful in guiding and interpreting such studies.

Mixing in Recovery Flows

The diffuser is still the largest assembly in a modern cw laser, and there has been a continuing interest in reducing its volume. The principal feature of supersonic diffusers is the complex multiple-shock boundary-layer interaction region wherein the flow is converted from a supersonic to a subsonic condition. The length of this region increases with the ratio of the incoming boundary-layer thickness to the pocket height, starting with a zero-length normal shock when no boundary layer is present. The side wall channels are thus critical to minimizing the overall length of a parallel pocket diffuser. Accordingly, an analytical and experimental study has been carried out of the flow in rectangular ducts with thick entering boundary layers and various inlet and outlet configurations. Attention was directed to

determining the channel height which gives minimum length for a specified boundary layer and recovery efficiency.

Control volume calculations were made wherein a turbulent flat plate boundary-layer was mixed with external flow to a uniform state, both in the absence of wall shear and with a choked exit caused by wall shear. The equations were solved algebraically to yield pressure recovery and choking limits as a function of external flow and boundary-layer to channel height ratios. Recovery is less than that provided by a normal shock in the free stream, and geometric diffusion and/or energization is necessary if normal shock recovery is required to balance the center pocket flow. Empirical correlations for the actual recovery process were explored as a first step to more detailed modeling.

Experiments have been carried out using the flow produced by a 7.5 x 10 cm cross section 2-D Mach-number 3 nozzle driven by either a 7.5 x 10 cm or 15 cm i.d. Ludwieg tube. A constant-area boundary-layer channel was used with a moveable plate that split off a diffusion passage connected to an atmospheric pressure muffler. Multiple expansion-wave reflections in the Ludwieg tube provided a staircase pressure history which could bracket the condition for unstarting the diffuser channel. The work has not been written up in detail, having been set aside in favor of the other activities of Section III.

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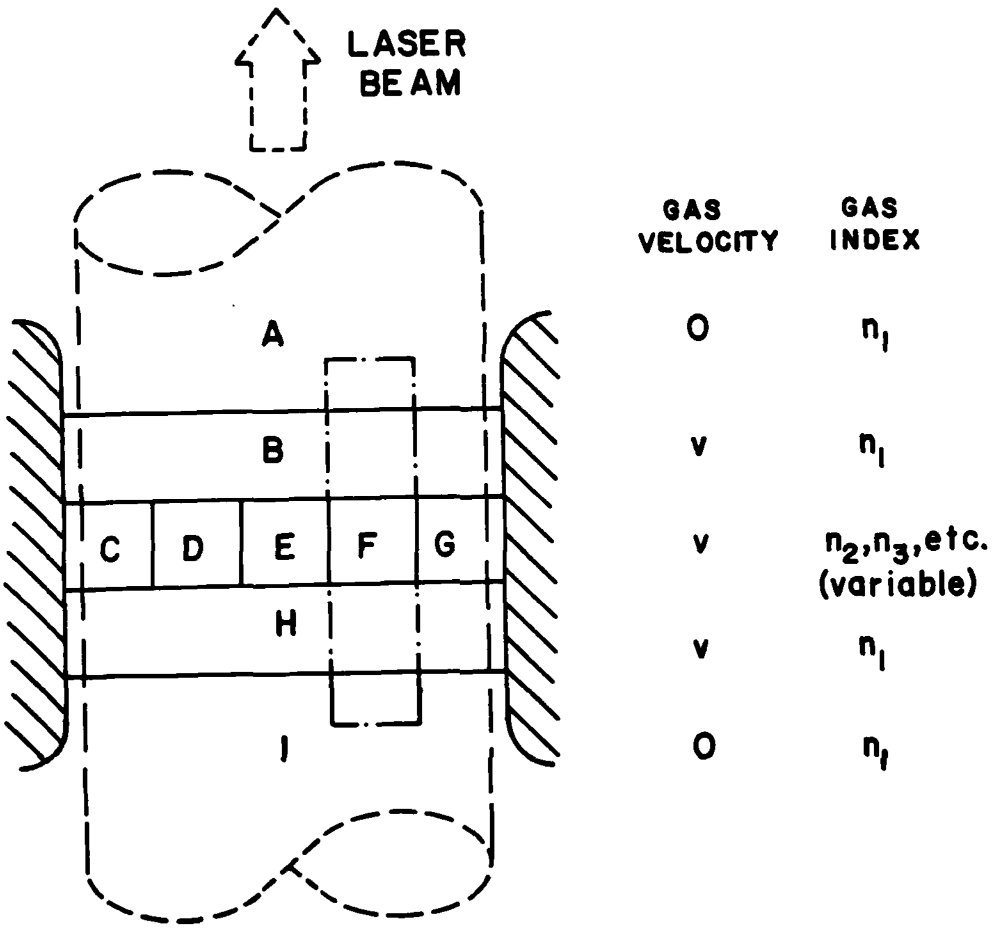
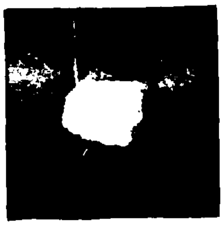
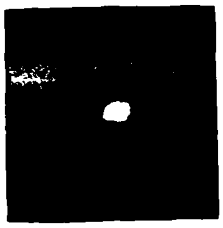


Fig. 1. A configuration for a gas jet array which appears to be promising for a practical phase control system. B through H are high subsonic jets with the flow direction out of the paper. A and I are regions of ambient air at rest.



(a)



(b)

Fig. 2. Photographs of laser beams exiting from the gasdynamic light guides, a) original light guide nozzle, b) improved nozzle with parabolic index density field.

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